ANALYSIS OF HOT SECTION FAILURES ON GAS TURBINES IN PROCESS PLANT SERVICE

by

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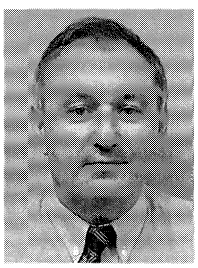

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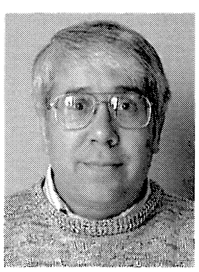

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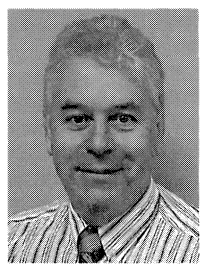
Mr. Daleo is a member of several professional societies, including ASM, TMS, and the ASME/IGTI Manufacturing, Materials, and Metallurgy Committee. He is the author of several technical publications and has participated in IGTI and other technical panel sessions on Gas Turbine Life Analysis and Repair. He holds a diploma in Metallurgical Engineering Technology from Mohawk College of Applied Arts and Technology, in Hamilton, Ontario.



James Wilson is Technical Director of BWD Turbines Limited, in Ancaster, Ontario, Canada. He has 25 years' experience in gas turbine related engineering projects. His background is in design engineering, mechanical evaluation, and failure analysis of turbine components, primarily rotating blades. Mr. Wilson was involved in all phases of the repair of gas turbine components at a repair company, including repair shop management, bid preparation, repair procedure specification and development, design of production and inspection tooling, calculation of repair limits, and specification of inspection criteria. He previously worked at Westinghouse Canada in mechanical design and procurement of gas turbine hot gas path components.

Mr. Wilson is a member of ASME and has authored several publications and participated in panel sessions on gas turbine management and repair. He holds a B.A.Sc. degree (Mechanical Engineering) from the University of Waterloo, Ontario and is a registered Professional Engineer in the Province of Ontario.

ABSTRACT

In-service failures of process plant gas turbines can have major economic consequences in terms of repairs and downtime. Following such an incident, steps need to be taken to avoid a recurrence. This is best accomplished through a formal analysis of the failure, and this paper discusses the key aspects of the procedure. Several case histories pertaining to hot section failures on mechanical drive and generator drive gas turbines in a variety of process plant applications are also presented. These provide a representative cross-section of the different failure mechanisms and range of causes that can be encountered as well as demonstrating the multidisciplinary approaches used to investigate the incidents. Lessons learned are highlighted.

INTRODUCTION

Gas turbines are to be found in mechanical drive and electric generator drive service in refinery, chemical, oil and gas facilities, and a wide range of other process plants. Despite the best efforts of the turbine designers, major in-service failures occasionally occur.

Following such an incident, the plant operator has three main priorities:

- Current operation
- Return to service
- Avoid recurrence

First of all, operational changes will have to be made to accommodate the equipment that has become unavailable. Secondly, manpower and hardware must be organized to dismantle, repair, and return the turbine to service. The third, and crucial priority, is to take steps that will avoid a similar occurrence in the future. This is best accomplished through a rigorous analysis of the incident. In such an analysis, the mechanism of failure is identified, root causes and contributing factors determined, and then appropriate solutions are developed. Failure analysis is the primary concern of this paper.

While recognizing that failures can and do occur elsewhere on the engine, the hot section is of specific interest here. The majority of gas turbine failures occur in this part of the machine where the hot section components (i.e., combustor liners, transition pieces, vanes (nozzles), and blades (buckets)) must operate at elevated temperatures with high stresses in a hostile environment (Boyce, 1982; Meher-Homji and Gabriles, 1998).

Typically, analysis of industrial gas turbine hot section failures demands a combined metallurgical-mechanical engineering approach to extract the maximum information from a failure event. This is reviewed in the paper. Deductive techniques such as fault tree analysis, can be useful in helping to understand the cause-and-effect relationships in the more complex incidents, and some discussion of this is also included.

A number of case histories of hot section failures on mechanical drive and generator drive gas turbines in process plant applications are presented. These serve as examples of the different failure modes, mechanisms, and causes that can be encountered as well as demonstrating the methods by which these were identified. Lessons learned are highlighted and, in addition to the strictly technical causes, shortcomings in the management of the equipment that allowed the conditions for failure to develop are discussed. In this respect, the root causes of many turbine failures can be traced to choices made, decisions taken, or events that occurred some considerable period of time, often years, prior to the actual incident.

Turbine failures are unexpected, unwanted, and the economic consequences in terms of downtime and repairs can be considerable. Nevertheless, such incidents can be used constructively to improve the design of the equipment and how it is operated and maintained. Successful failure avoidance is achieved through an experienced team using proven methods to properly analyze the causal factors. The recommended solutions must then be committed to and implemented correctly.

TURBINE HOT SECTION DEGRADATION MECHANISMS

Turbine hot section components degrade during service (Daleo and Boone, 1996; Bernstein, 1998). This degradation occurs in different ways for different modes of turbine operation; creep, oxidation and hot corrosion are, typically, the main life limiting factors in continuous duty machines, while thermal-mechanical fatigue is the factor of most concern in machines used in intermittent service or peaking operation. Other damage mechanisms such as high cycle fatigue, foreign object damage (FOD), erosion, and wear can also be of significance. Often, the situation is quite complex with several damage mechanisms acting in combination. A brief description of each of the main mechanisms is provided in APPENDIX A of the paper.

The forms of hot section component degradation mentioned above tend to be gradual, time dependent processes that can usually be effectively managed through programs of inspection and maintenance. However, if the degradation is somehow unanticipated, is more than expected, or is allowed to go too far, component failure can result.

The components in the hot section of a gas turbine can also be subject to damage in more acute (and often dramatic) ways. The causes are typically associated with variability in fuel composition/heat value and with fuel system/nozzle faults. Such occurrences can give rise to combustion upsets in which both combustor and turbine sections are exposed to abnormally high or uneven gas temperatures and, in extreme cases, to fires and explosions.

Primary and Secondary Failures

In understanding failure sequences in turbines (and other turbomachinery), it is necessary to consider the primary (or initiating) failure and the secondary (or consequential) failures/damage. The potential exists for widespread secondary damage when the primary failure, notably involving the fracture of a rotating blade, results in the release of pieces into the gas path. Depending on the location at which this occurs, the outcome can be damage to a few neighboring components or catastrophic failure of the entire turbine section, commonly referred to as a turbine "wreck."

Some circumstances have been encountered where additional secondary damage occurred after the turbine operator, unaware of the internal damage just caused to the machine, attempted one or even several restarts resulting in "churning" of the loose parts and debris.

The implications of secondary damage/failure are twofold. First, the greater the extent of the damage, the higher the repair costs and longer the downtime will be. From the point of view of the failure analysis, the site of the primary or originating failure may have become smeared (plastically deformed), broken up, or even destroyed completely. This can significantly complicate the task of the failure investigators, increasing the effort required to sort and examine components and pieces to locate, and distinguish those features existing at the start of the failure sequence from damage inflicted during subsequent events. In some circumstances though, data pertaining to secondary damage can be usefully extrapolated back to provide clues as to the location/nature of the primary failure.

Ideally, we would like to find evidence that positively identifies a particular component as being the one that failed first. Subsequent efforts could then be focused on understanding exactly how and why this component failed. However, where such an identification cannot be made due to the severity of the secondary damage, the next best outcome is to find clues indicating prior cracking, distress, or some other deficiency across a number of the components that could have lead to a failure consistent with that observed.

Figures 1 and 2 contrast the impact damage environment in a large, utility-type gas turbine and a smaller, mechanical drive turbine, respectively, resulting from the failure of a rotating blade. Despite the catastrophic airfoil damage on all four rows of blades shown in Figure 1, it was evident that the failure originated in the first row and, moreover, the particular blade involved was readily identifiable due to its different fracture surface location (in the root section), pattern, and coloration. The mechanism of the primary failure was subsequently identified as being high cycle fatigue related. In the mechanical drive turbine, Figure 2, all the hollow-cored bucket airfoils on the single-stage compressor turbine were fractured very similarly as a result of the impact cascade. Despite careful examination of all the buckets in the set, the one on which the initial failure and breaking out of a piece of airfoil occurred could not be positively identified. Nevertheless, a probable mechanism and cause for the primary failure was successfully determined (as will be seen later in the case history for this incident).

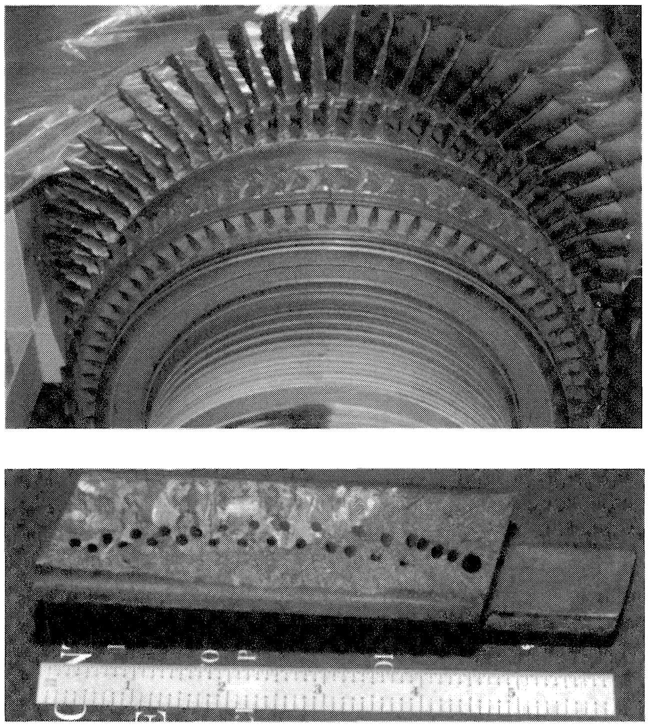


Figure 1. Damage to All Four Rows of Blades in Large, Generator Drive Gas Turbine. (The fracture surface (in the root section) of this particular blade is shown in the lower photograph.)

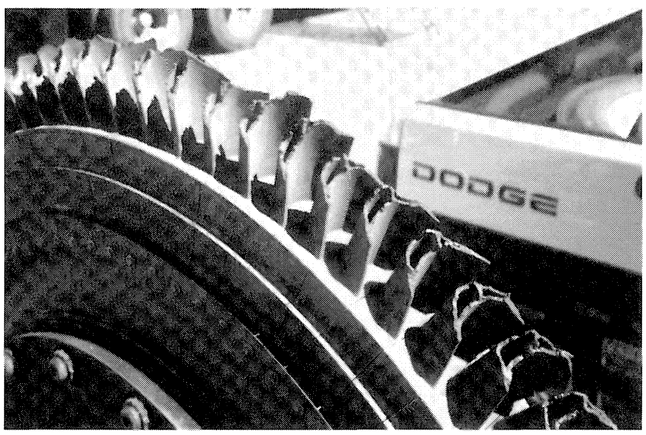


Figure 2. Damage to Hollow-Cored First Stage Turbine Buckets in a Mechanical Drive Gas Turbine.

FAILURE INVESTIGATION AND ANALYSIS

Objectives

The goal of a failure analysis on a gas turbine is basically the same as it would (or should) be for any critical process machinery: avoid a recurrence. This means not only avoiding the *particular* failure experienced, but avoiding this *kind* of failure (Witherell, 1994). Accordingly, there may be implications beyond the incident machine. If there is other similar equipment at the plant or within the organization, then these should also be considered in the post-failure strategy.

It is insufficient to identify solely the metallurgical mechanism of failure (creep, fatigue, etc.); the mechanical/operational cause(s) and contributing factors must also be determined. Then, specific solutions or steps, tied to design, operation, inspection, overhaul, maintenance, purchasing, or related practices under our control, can be identified that would address the causal elements.

Organization

Experience has emphasized the value of a multidisciplinary approach to conducting failure analyses in which a team of unbiased personnel working independently of outside influences are given adequate time and resources to conduct the necessary investigatory tasks.

Analysis of failures of gas turbine hot section components demands a fairly specialized background. Specifically, an understanding of the metallurgy and behavior of superalloy materials and associated protective coatings, coupled with an appreciation of the mechanical and thermal design characteristics of stationary and rotating turbine components. Combining specialist expertise and resources in these areas with the turbine user's specific knowledge of plant and equipment operational characteristics, inspection, and overhaul practices, as well as the incident itself, will generally represent the best approach by which a complex hot section failure can be analyzed (for example, Lowden and Liburdi, 1985).

Strictly speaking, the followup to a failure incident comprises "investigation" and "analysis" phases (Witherell, 1994). The investigation typically involves the initial survey and characterization of the problem in the field, documenting conditions and observations, and the identification and gathering of failed parts, nonfailed parts, and other potentially relevant data. The analysis phase, on the other hand, involves extracting further information concerning the failure via the laboratory analysis of the selected parts, modeling and calculation work, cause-and-effect charting, etc., to allow a full understanding to be gained of what occurred and why. All the information is organized and reviewed, conclusions drawn and appropriate corrective measures developed from these.

Preserving the Evidence

Gathering and preserving evidence after a failure are crucial steps, and time is of the essence. The first priorities should be with those data that could be considered "volatile" or time sensitive in the sense that these could readily become discarded, rearranged, or forgotten about. Accordingly, it is important to commence the onsite phase of the failure investigation as soon as practical after the incident to minimize the opportunities for evidence degradation and loss. Relevant data will be people, parts, and paperwork related, i.e., witness recollections, failed and intact components, control system histories, instrument charts, etc.

Wherever possible, the failure investigators should have the opportunity to appreciate the "bigger picture" by reviewing the overall appearance of the wrecked turbine and relative positions of the components, as well as just individual parts or pieces. The taking of a video or photographic record of the opening up and dismantling of the turbine represents an extremely valuable method of preserving the as found condition of the equipment for ongoing review. Ideally, the failure analysis should dictate when equipment dismantling and repairs can occur. More realistically, however, the post-failure priorities of getting the failed machinery back online and preserving evidence must be balanced, recognizing that repair efforts will likely compromise information.

Despite the best efforts of turbine users to gather and preserve evidence after a failure, it is not uncommon for the material and other data actually available for analysis to be significantly less than the ideal.

Fault Tree Analysis

A systematic approach to failure analysis, based on pursuing cause-and-effect relationships, significantly enhances the chances that the root (primary) causes and important contributory factors will all be successfully identified (Bloch and Geitner, 1997; Witherell, 1994). Preparation of a causation diagram, in which the possible failure sequences are logically represented, can be extremely useful not only as an aid during the investigation itself, but in helping to communicate the findings to others. This means convincing plant management, insurers, and other concerned parties that all potential causes have been considered, the conclusions reached are plausible and consistent with actual experience, and the recommended actions will address the problem areas.

Causation diagrams based on the deductive, fault tree method have been found to be particularly useful (for example, Perez, 1995). In a fault tree, the primary event, problem or damage condition under consideration is progressively traced "downward" through all the possible cause-and-effect chains. The diagram is put together based on consideration of the specific design and operating circumstances of the unit, known failure mechanisms for gas turbine components, and the experience base of the investigators concerning previous failures and problems.

Since fault trees can be quite extensive, only portions can be included in this paper. Parts of two representative diagrams are shown. The diagram, shown in Figure 3, was actually developed following another fault tree put together by the plant investigation team subsequent to a catastrophic turbine failure (Case History B). This first fault tree had been used to help systematically eliminate turbine operational factors, such as instrumentation and control system faults, as causal factors in the failure, thereby narrowing down the range of possibilities to mechanical degradation of components. These issues were then specifically addressed in the second phase of the investigation for which the fault tree here was created. Figure 3 shows an intermediate "branch" of the tree concerned with failure by creep rupture. Other portions of the diagram considered high cycle fatigue, foreign object damage, etc.

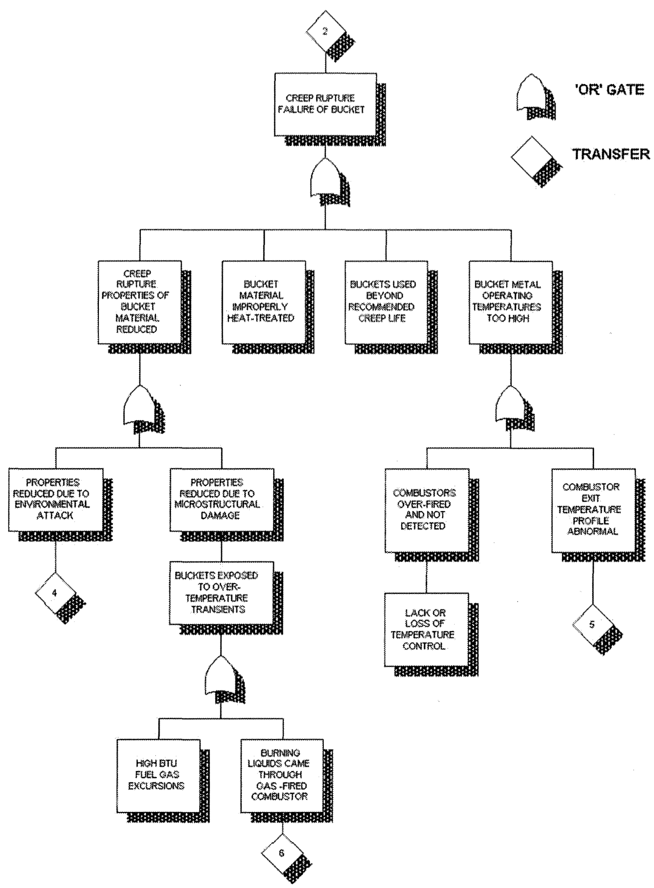


Figure 3. Intermediate Branch of Fault Tree Diagram Used to Analyze the Failure Described in Case History B.

Figure 4 shows the "top" part of another fault tree. This diagram, prepared for Case History D, explored the potential causes of severe overheating damage to a row of cooled turbine nozzle vanes. Cause-and-effect chains were developed for exposure of the vanes to excessively high gas temperatures and for failures of the cooling on the vane that comprised impingement, convection, and film features.

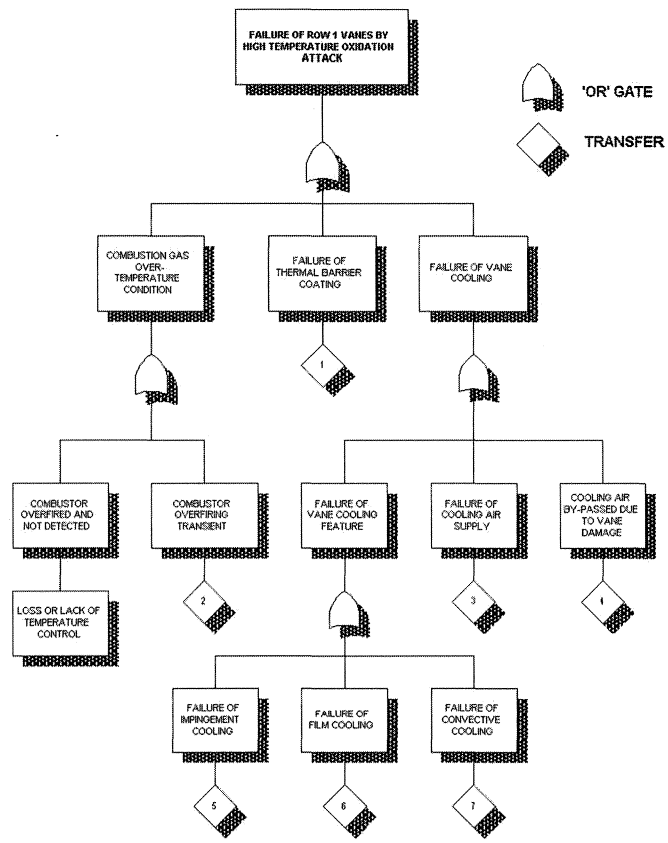


Figure 4. Top Portion of Fault Tree Diagram Used to Analyze the Overheating Failure of Cooled Vanes Described in Case History D.

In order that the causation diagram is not overly wide-ranging, it is most useful to prepare it after a preliminary assessment of the failure has been made. For example, it is usually evident early on whether the primary damage observed was the result of an overheating/burning mechanism or was "mechanical" in nature. If the data are not consistent with the former, then this avenue need not be pursued in the fault tree diagram. Similarly, little or no cause-and-effect analysis should be necessary on the secondary damage. Should new information be uncovered later on, however, the fault tree can always be developed further.

Use is made of the fault tree diagram in the following manner. Branches of the tree not supported by the factual information arising out of the metallurgical, mechanical engineering, and other analysis activities are eliminated from active consideration. The process of narrowing down the possible cause-and-effect chains continues until a most probable scenario for the failure is formulated.

FAILURE ANALYSIS ACTIVITIES

The kinds of examinations conducted during a failure analysis will vary considerably depending on the nature of the failure, components and materials involved, and other factors. No two failures are exactly alike. Nevertheless, typical activities in gas turbine failure analyses can be identified and these are highlighted below.

Metallurgical Analysis

Metallurgical analysis of the failed components, nonfailed components, and other material as necessary, is central to machinery failure analysis. The following metallurgical activities are typically conducted for turbine hot section incidents:

- Visual inspection
- Nondestructive examination
- Chemical analysis of alloy
- Analysis of deposits on gas path surfaces
- Fractographic analysis of fracture surfaces
- Analysis of coated surfaces
- Metallographic analysis
- Mechanical properties testing

The visual inspection and then nondestructive examination (to find hidden and secondary cracking, etc.) are used to identify those components that have features worthy of further and more indepth metallurgical evaluation. Typically, the nondestructive examinations will utilize a high sensitivity fluorescent penetrant technique, though other specialized methods such as eddy current and radiography might be employed depending on the situation.

As part of the visual inspection, the identification information provided on each component (serial number, material code, part number, manufacturer logo, etc.) should be noted. This is not only necessary for tracking purposes but, in conjunction with purchasing, installation, and other records, will help to confirm the origins of the components. This information can be especially relevant when the parts in question were replacements.

Fractographic and metallographic evaluations involve the use of low power stereoscopic imaging and optical and scanning electron microscopy. Material mechanical properties are usually determined using tensile, creep, and impact tests. Chemical analysis is typically performed using wet chemical, energy-dispersive X-ray, and X-ray diffraction techniques.

Estimates of component metal operating temperatures often represent very valuable pieces of data in the investigation of a hot section failure and can be derived from metallurgical analysis of alloy and coating microstructures (Ellison, et al., 1998).

Mechanical Analysis

Mechanical analysis can represent an important aspect of failure analysis by evaluating the design of the component under consideration for susceptibility to failure and assisting in the interpretation of the metallurgical findings. This involves performing calculations to determine stress patterns, temperature distributions, or vibrational response as pertinent to the situation. Typically, finite element methods are used, though standard formula can be useful. The required dimensional information is retrieved from intact components while performance data may be obtained from published sources and actual operating records.

Calculated results can be correlated with the actual observations pertaining to the location and mode of damage or failure on the component.

CASE HISTORIES

The following five case histories represent a cross-section of turbine hot section failures from the authors' experience.

The first two cases, A and B, involved the same basic model of widely used, heavy duty, 14,600 hp rated, mechanical drive gas turbine. The same components (single-stage compressor turbine rotating buckets) failed in a similar manner. However, the analyses showed that the mechanisms of the primary failure were actually different, though the two incidents shared strong similarities with respect to their root causes.

Case History A
High Cycle Fatigue Failure of Turbine Buckets

The turbine in this case history was in service at a natural gas transmission pipeline compressor station. After many years of successful operation, the turbine was overhauled and operated for a further eight months, though at a reduced power setting. On being returned to full load, however, the unit failed after only a few hours.

The failure was characterized by loss of airfoil material on all the first stage buckets down to 60 percent to 70 percent height (Figure 5). The last inch of the trailing edge tip was still intact in most cases.

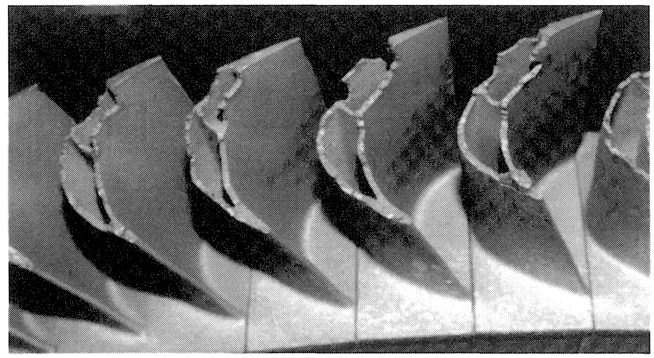


Figure 5. Failed First Stage Buckets. (The volume and shape of airfoil material loss was very similar on all the buckets in the row.)

The pertinent overhaul documentation was reviewed and it was found that the failed buckets had been a replacement set made up from three previously used groups of components. However, it appeared that refurbishment on these had been done with incomplete knowledge of the metallurgical reasons why the components had originally been retired.

The metallurgical analysis revealed extensive, pre-existing oxidation/corrosion damage remained beneath the refurbished aluminide coating on the external side of the airfoil (Figure 6), while the original platinum modified aluminide coating was never actually removed from the inside surface. Heat treating the buckets in this condition had resulted in localized melting and excessive diffusion of the coating into the IN-738LC base metal. In thin-walled components, this not only locally destabilizes the alloy microstructure, but also results in a thick, brittle layer on the internal surface. While acceptable creep rupture properties were obtained, the regenerative heat treatment cycles used did not fully restore the IN-738LC microstructure (Figure 7).

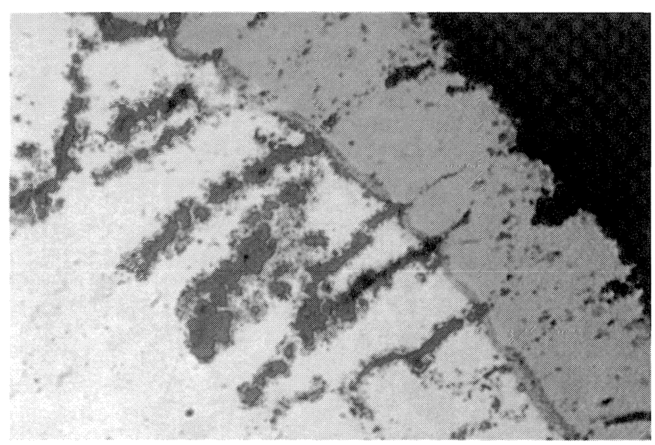


Figure 6. Photomicrograph Illustrating the Damage to the Base Metal Below the External Coating on One of the First Stage Buckets.

The set of buckets was also found to be made up of castings with two different airfoil styles. One of these had evidently been

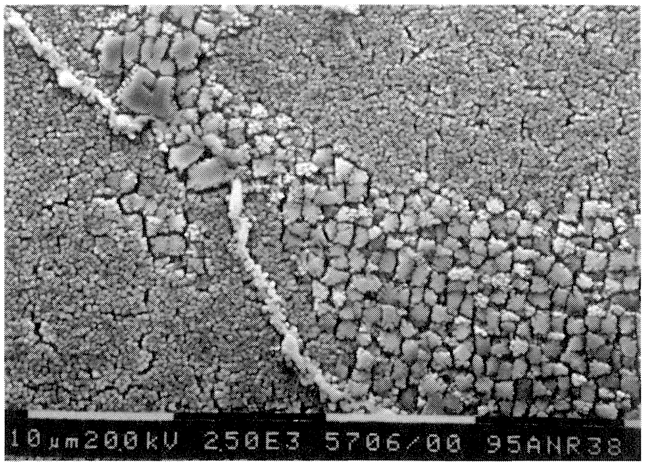


Figure 7. Scanning Electron Micrograph of First Stage Bucket Alloy Illustrating That the Component Had Not Been Properly Heat Treated. (The microstructure consisted primarily of a single size gamma prime distribution with small isolated islands of the normal duplex gamma prime precipitate structure.)

manufactured using a larger rear cavity core producing an approximately 25 percent thinner wall on the convex side of the airfoil. Radial cracks propagating down from the airfoil tip at the trailing edge of the rear internal cavity were present on these components. No such cracking existed on the buckets with the thicker walls.

A mechanical analysis was performed using a three-dimensional finite element model of the bucket, and vibrational frequencies and mode shapes were calculated. The Campbell diagram showed that various resonant conditions were present in the operating range. However, high relative stresses were only evident in the crack locations when the bucket vibrated in Mode 9 (an axial bending mode).

It was concluded that the cracks found in the tip regions of the thin-walled buckets had probably developed and grown slowly while the turbine was operating at lower power. The high power and speed condition excited the Mode 9 vibration and drove the cracks rapidly until a piece of airfoil on one of the buckets broke out (this particular bucket could not be positively identified). The other buckets then fractured readily when struck by debris in the ensuing impact cascade. The poor surface and microstructural condition of the buckets contributed to reduced fatigue strength and impact resistance.

Discussion of the root cause of this incident is given later in conjunction with that of Case History B.

Case History B

Oxidation-Assisted Creep Failure of Turbine Buckets

This turbine was in recompression service at a natural gas processing plant. Five days after restart following a plant outage, the unit experienced an automatic shutdown due to high exhaust temperature. There were no unusual prior operating conditions. Following one partial restart, the turbine failed to restart at all. At the time, the unit had accumulated around 26,000 fired hours since last being overhauled.

When the turbine case was removed, it was discovered that airfoil material had been lost down to about 30 percent to 40 percent height on all first stage (compressor turbine) rotating buckets (Figure 2). The volume and shape of material lost was similar on all buckets, though trailing edge sections were still intact on a few components. The other turbine section components sustained significant damage consistent with impacts with high-energy debris. The "evenness" of the damage on the buckets somewhat resembled that which is typically observed when caused by a burning incident, but it was soon established that the failure was strictly mechanical in nature.

It was clear that failure of the first stage buckets was the primary failure. The fractured surfaces were examined and the fracture mode was characterized as being of a brittle, intergranular nature. There was no evidence of high cycle fatigue. The examination was complicated, however, by the presence of many areas where the intergranular surface had been locally smeared producing a smoothed surface with striations that closely resembled the features usually associated with fatigue crack propagation.

The pattern of damage on the first stage buckets was again consistent with a cascading (or "domino effect") impact overload mechanism initiated by the failure and breaking out of a section of the upper airfoil on one of the buckets. Fracturing of the airfoils would have occurred readily given the hollow design with walls thinning toward the tip, the relatively brittle characteristics of the service-exposed alloy, and prior cracking. The loss of a significant amount of airfoil material on all the rotating buckets caused a sudden reduction in the energy extraction (temperature drop) across the first stage, producing the high temperature excursion in the exhaust gas that tripped the turbine.

Metallurgical analysis revealed that on around 10 out of the set of 80 buckets, extensive oxidation of the IN-738LC alloy grain boundaries and axial cracking existed on the suction side surfaces behind the leading edge, just below the main fracture surface. The cracks extended almost completely across the airfoil section (Figure 8). These did not show up during a borescope inspection of the turbine just five days prior to the failure, though based on the oxide coverage of the fractured surfaces, the cracks had indeed been present and growing for some time. The material immediately below the cracks contained numerous secondary cracks running in parallel. Some of these were surface connected and oxidized, while others appeared unoxidized.

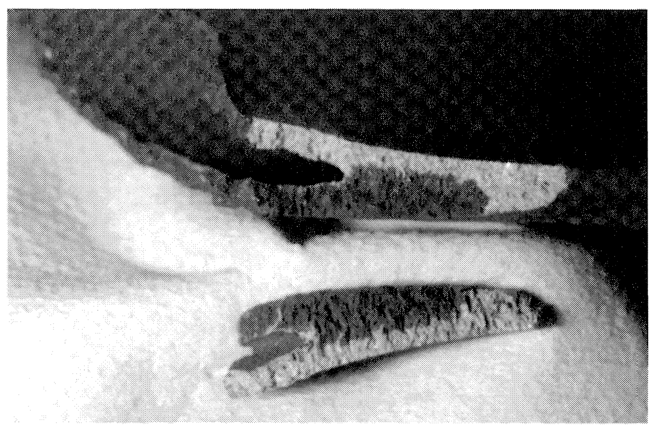


Figure 8. Oxide-Covered Surface of Mechanically-Opened Creep Crack in the Suction Side of a First Stage Bucket Around from Leading Edge.

Measured creep rupture properties on material removed from the (lower operating temperature) root/shank sections of sample buckets, representing two of three different source/manufacturing lots making up the set, were significantly below the minimum standards for the alloy, indicating incorrect original heat treatment. The prior history of the parts, which were non-original equipment manufacturer (OEM) and purchased as used and refurbished, could not be located. However, there was evidence to suspect that some of the accumulated creep and oxidation damage had been sustained during a previous service exposure in a different turbine and was not properly repaired.

Based on the degree of cracking present on some of the buckets, a premature failure appeared to be inevitable. However, it is thought that a slightly higher rotor operating speed after restart from the unit outage, brought about by aggressive cleaning of the axial air compressor, subjected the bucket airfoils to an increased level of centrifugal stress sufficient to accelerate the growth to failure of an existing creep crack, after just a few additional days of operation.

Replacement Parts Quality Issues

In case histories A and B, the root cause of failure was traced to problems with the quality of refurbished used buckets installed as replacements at the previous major overhaul of the turbine.

When refurbished used parts are being considered as a replacement set, it is important to have a knowledge (supported by appropriate documentation) of the prior operating and repair history of the parts. This would include:

- Previous operating hours
- Operation mode
- Type and severity of damage sustained
- Number of times repaired
- Where repaired
- Repair processes used

Without such background information (and it can often be hard to find), the ability of the parts to perform reliably in the new service application cannot be properly judged. Moreover, sets of refurbished used components are sometimes made up from parts drawn from a number of different sources or manufacturing lots. This can increase the opportunities for wide variability in dimensional and material quality, and significantly complicate the task of properly verifying the acceptability of the full set. Clearly, it can take just one "bad" component to wreck an entire turbine section.

Good judgement should be exercised or expert help sought in making repair or replacement decisions for critical turbine components (Natole, 1995). These decisions should not be based solely on price or delivery. The turbine user should prepare specifications to clearly define what is expected in terms of processing, critical dimensions, etc. The repair work should then be monitored in detail and the final quality verified before the set of parts is considered ready for installation in the turbine. This verification should take the form of destructive examination of a sample component (or components as necessary) for which alloy and coating microstructures and mechanical properties are analyzed.

Unless the turbine user takes the above steps, risks may be taken on with respect to component integrity that are totally inappropriate for a turbine in a high reliability service application.

Following the incidents in Cases A and B, the organizations involved undertook reviews of their procurement practices for critical hot section components.

Case History C

Accelerated Creep Failure of Turbine Buckets
Caused by Previous Over Temperature Event

This case history involved an earlier 9300 hp model of the gas turbine in cases A and B. The unit was used to drive a refrigeration compressor at a refinery.

A catastrophic failure of the first stage turbine buckets occurred. All the bucket airfoils (which were of solid design) fractured at approximately mid-height (Figure 9), and impact damage was sustained by the downstream gas path components.

The primary fracture on the buckets had propagated in an intergrannular mode across the entire airfoil section. The fracture surfaces at the leading edges appeared typical of high temperature creep or thermal-mechanical fatigue (Figure 10), while the remainder was more characteristic of intermediate temperature creep rupture crack growth and brittle impact overload. Evidently, one bucket airfoil had failed, initiating an impact cascade that resulted in the fracture of the other buckets in the row.

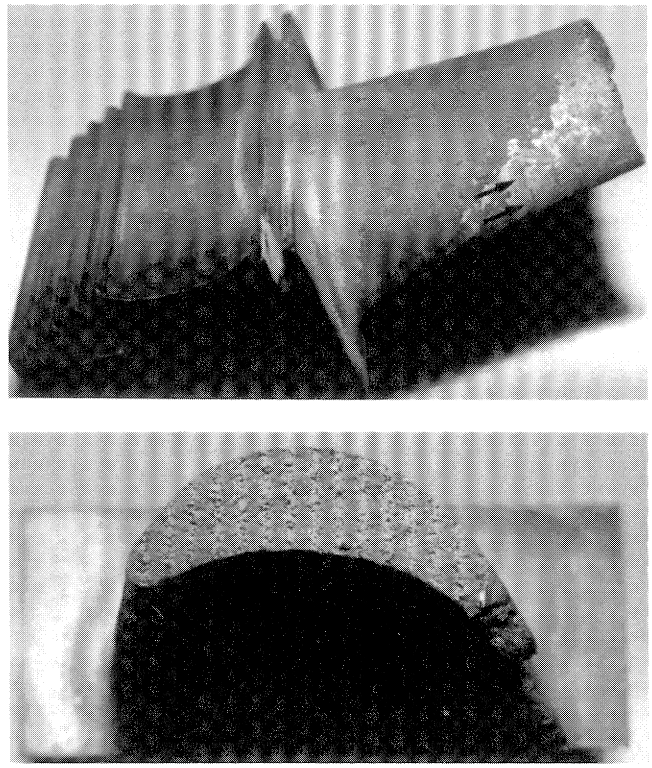


Figure 9. Failed First Stage Bucket. (The upper photograph shows that the aluminide coating was missing below the fracture surface and a secondary crack was present (highlighted by arrows). The mode of fracture was intergranular across the airfoil section (lower photograph).)

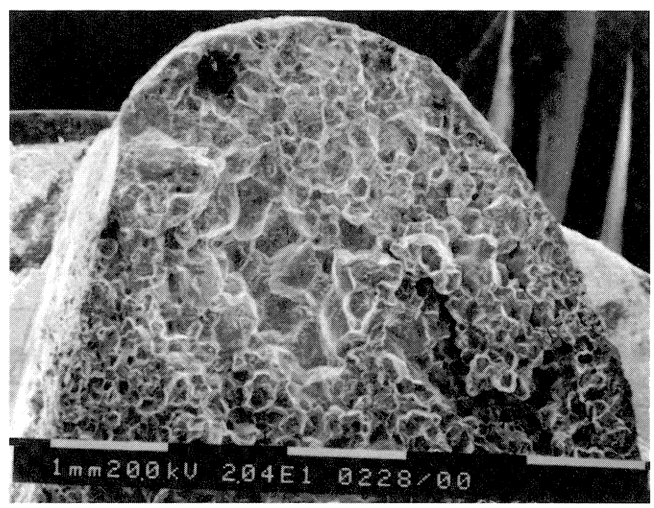


Figure 10. Scanning Electron Fractograph of Failed First Stage Bucket Leading Edge. (The fracture had propagated in an intergranular mode.)

The coating on the buckets had been lost in the leading edge region adjacent to the fracture surface, but the base metal was not oxidized. Microstructural damage and axially oriented cracks were observed at the leading edges on all buckets (Figure 11). No damage was present in the trailing edge regions, however.

The estimated temperature of the bucket metal was only 1380°F at the nominal firing temperature of 1450°F. However, it was apparent that the buckets had experienced much higher temperatures at some point in their operating history. The over

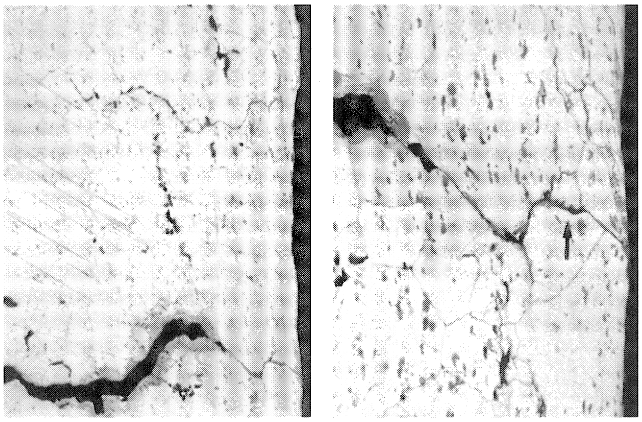


Figure 11. Photomicrograph Showing Microstructural Damage and Cracking in the First Stage Bucket Leading Edge Region. (Left photograph, ×40; right photograph, ×100)

temperature was evidently hot enough to cause the observed metallurgical damage (greater than 2150°F) and melting of the coating/base metal diffusion zone (greater than 2175°F to 2300°F). It was of insufficient duration to cause oxidation of the base metal, after the coating was lost, as well as bring about any similar changes in the airfoil further away from the leading edge region. The latter aspect was investigated via a simplified heat conduction/convective model of the bucket, demonstrating that the duration of the high temperature transient was likely no more than 30 seconds.

Given that enough refinery gas fuel could not be admitted to achieve the required temperatures at the base load condition, the most plausible cause of the short duration over-temperature condition was that burning liquids came through the combustor and impinged on the front of the rotating buckets. The locally elevated rates of heat transfer assisted in the raising of the metal temperatures to the levels necessary to produce the damage to the coating and alloy microstructure. The cracks found in the leading edge of numerous buckets likely initiated as a result of the metallurgical damage and reduced properties caused by the overtemperature exposure. The cracks subsequently progressed across the airfoil sections by the mechanism of creep until one of the buckets failed in overload.

Based on the analysis, the turbine operator was prompted to review provisions in the fuel gas system for preventing flammable liquids reaching the turbine combustor.

Case History D

Overheating Failure of Cooled Turbine Vanes

This case involved a 50 MW, geared, natural gas fired industrial gas turbine at a paper products facility. The unit provided electric power and a supply of hot gas for process purposes.

The turbine came off a major overhaul and ran under uprated (increased firing temperature) conditions. After a number of months of operation, exhaust temperature spread and disk cavity temperatures were observed moving high. An outage was taken and it was discovered that all the first stage cooled nozzle vanes had sustained severe and irreparable overheating damage. The damage was concentrated on the suction side of the airfoil and significant breakthrough and breaking away of wall sections had occurred, Figure 12.

As part of the failure analysis, a fault tree was created (Figure 4). Based on the condition of the combustor baskets, transition pieces, first stage rotating blades, and other evidence, it did not appear that the nozzles had been exposed to abnormally high gas temperatures. A cooling failure scenario was more probable, therefore.

The vane airfoils were individually cooled by air diverted from the compressor discharge. The coolant entered each vane at the

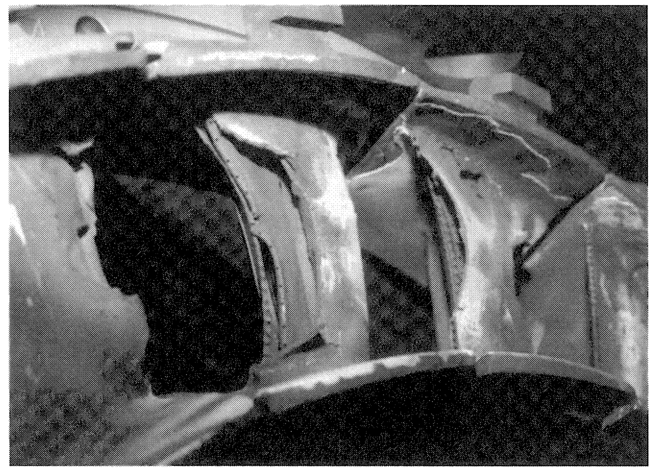


Figure 12. Row of First Stage Vanes Showing Burning Damage as Viewed from Trailing Edge Side.

outer shroud into two full impingement cooling inserts. Spent impingement cooling air exited the vane through three rows of holes providing film cooling on the airfoil walls and a row of ejection slots along the trailing edge. Two of the rows of film cooling holes are located on the suction side of the airfoil, just around from the leading edge, and are designated S1 and S2. The other row, P1, was on the pressure side near the trailing edge.

In examining the set of vanes, particular attention was given to those components that were among the least damaged and, therefore, could provide better opportunities for determining where the failure originated. Several vanes were subsequently identified containing features that appeared to be representative of different stages in the progression of the damage. From these, it was evident that local high temperature oxidation attack had started just downstream of the S1 film cooling holes at the outer shroud end of the row (vane in Figure 13). The airfoil wall became breached and as the damage progressed along the row of holes, the cooling air flow became more disrupted, exacerbating the overheating situation and extending the area of damage. The vane cavity became exposed to the hot gases leading to the damage in the trailing edge region apparent in Figure 12.

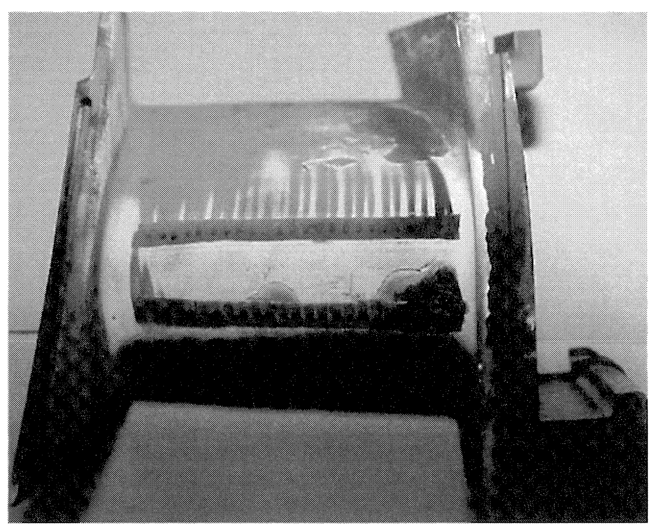


Figure 13. First Stage Vane Showing That Localized Oxidation Attack Had Commenced at Outer Shroud End of the First Row of Suction Side Film Cooling Holes.

Powdery fines ingested by the engine compressor during the normal course of operation, and subsequently deposited on the internal and external surface of the vanes, provided some useful data about how the cooling features had been performing. No evidence was found to suggest that any restricting or bypassing of the cooling air flow had been occurring. Streak-like markings extending over the thermal barrier coating on the external surface and corresponding to the trajectories of the air ejected from the film cooling holes (Figure 13) provided the most important clues. The patterns associated with the S2 and P1 holes were consistently well defined and persistent in the downstream direction with little lateral interaction. The S1 holes exhibited markedly different behavior, however. Surface trajectory patterns were not always present and, where they were, tended to be short and diffuse, suggesting that the mainstream gas had been getting around and under the cooling air jets causing these to become mixed-in rapidly.

Based on the location of the damage, the observed cooling air flow patterns and results from simulations on a finite element based heat transfer model of the vane, it was concluded that aggressive oxidation attack had occurred. This was due to locally excessive metal surface temperatures that had been caused by the failure of the cooling air ejected from the S1 row of holes to form a sufficiently persistent and protecting film over the airfoil surface immediately downstream. It appeared that this feature of the vane cooling design exhibited only marginal effectiveness under the uprated operating conditions. Among the contributing factors was that the S1 holes were located in a high curvature part of the airfoil, resulting in the angle of the ejection holes being unusually steep.

Another important aspect of the failure was that, while all vanes in the set sustained damage, there was significant variability in the degree of damage due to differences in the age and condition of the individual components at the beginning of the service period in question. In general, the damage on the older vane segments was significantly worse due to reduced safety margins on leading edge wall thicknesses (Figure 14). The uncoated internal and cooling hole surfaces had been oxidizing and reducing the ligaments between the holes, which also contained small thermal-mechanical fatigue cracks.

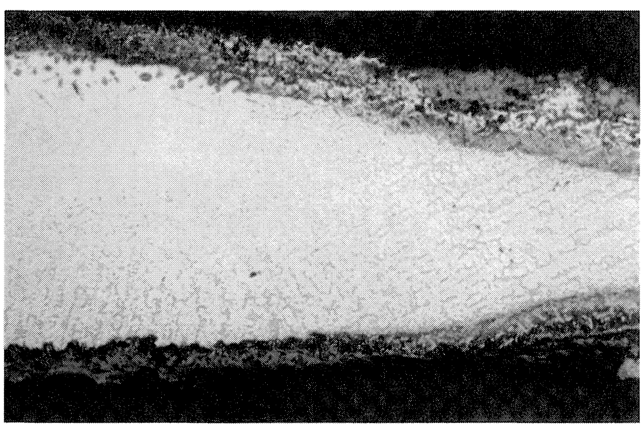


Figure 14. Photomicrograph Showing Level of Pre-existing Oxidation Damage on Internal and External Surfaces of First Stage Vane Wall Section in the Vicinity of the First Row of Suction Side Film Cooling Holes. (Photograph, ×60)

Essentially, the weakened line of cooling holes acted as "perforations" along which the failure readily progressed. The inclusion in the vane set of components that had already accumulated 50,000 hours of service and been through four repair cycles was, in hindsight, probably not an appropriate strategy for a turbine about to be operated under even more demanding temperature conditions.

Case History E
High Cycle Fatigue Failure of Power Turbine Blade
Due to Unanticipated Resonance Condition

This case involved a 8500 hp rated, two-shaft, industrial gas turbine driving a seawater injection pump at an oil and gas production site.

A last stage power turbine blade manufactured from Nimonic 90 failed after about 24,000 hours of operation. The fracture occurred in the root section of the blade (Figure 15) and a number of other blades were identified as having cracks at the same location. Changing process requirements at the site had dictated that the driven equipment run at lower power and speed levels. The failure of the blade occurred after operation of the gas turbine under these new conditions.

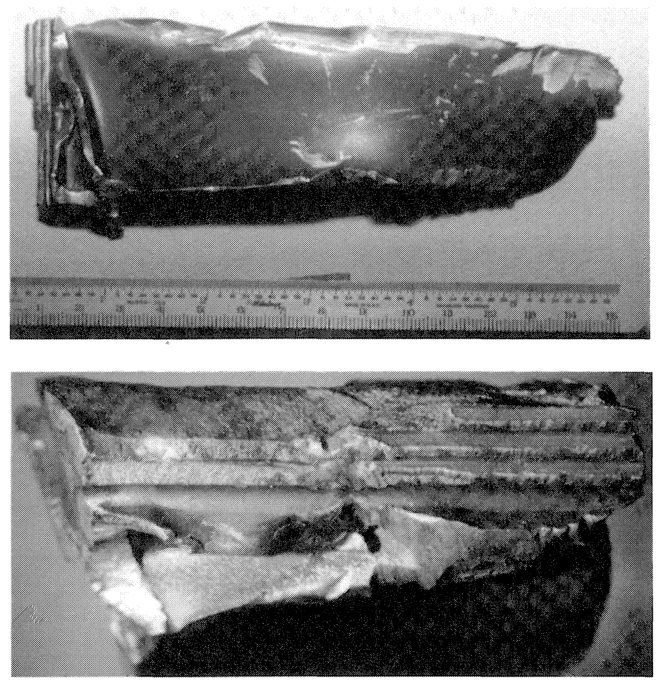


Figure 15. Failed Last Stage Power Turbine Blade. (The top fir tree serration crack and failure path along the second serration are seen.)

The blade root exhibited multiple fracture initiations on both first and second root serrations. The blade had failed across the second fir tree serration. Metallurgical examination of fracture surfaces and cracks revealed features consistent with high cycle fatigue. Fatigue striations were clearly visible and exhibited a repeating pattern at approximately eight-cycle intervals (Figure 16). No material defects or other forms of degradation were found.

While having found clear evidence identifying high cycle fatigue as the metallurgical mechanism of failure, additional information was necessary to help understand the cause. Accordingly, a mechanical analysis was undertaken to determine whether some feature of the design had predisposed the power turbine blade to fail in fatigue.

A three-dimensional finite element model of the blade was created. The first six vibration frequencies and corresponding mode shapes were calculated for the model. The Campbell diagram presentation of the results is given in Figure 17, with the interferences of interest highlighted. A resonance existed in the first tangential bending mode at 10,200 rpm with the third harmonic of running speed. A different resonance existed in the second tangential bending mode at 9100 rpm with the eighth harmonic, which corresponded to the number of combustors on the engine. It is likely that the first mode resonance initiated cracks in

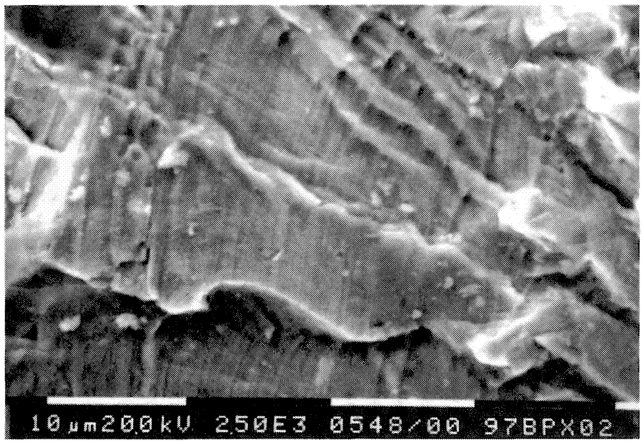


Figure 16. Scanning Electron Fractograph of Cracked Last Stage Power Turbine Blade.

the failed blade during short term operation transients to 10,300 rpm, followed by propagation to failure under resonance conditions for much longer times at 9100 rpm. The cracked blades probably initiated cracks due to the excitation during operation at the lower speed. The location of the calculated highest dynamic stresses correlated with the observed crack initiation points.

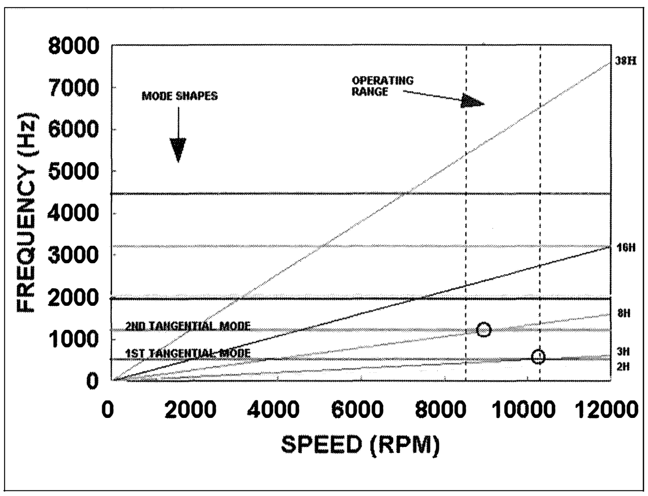


Figure 17. Campbell Diagram for Last Stage Power Turbine Blade. (The interferences of interest are highlighted.)

The freestanding design of the last row of power turbine blades was somewhat unusual for a variable speed machine in which it is often impossible to avoid some resonant conditions in the operating range. Lashing wires or interlocking tip shrouds are typically utilized to control blade vibrations. Prompted by the failure analysis described here and further occurrences on turbines at the same site and elsewhere, the turbine manufacturer acknowledged that a problem existed and undertook a complete redesign of the blade.

CONCLUSIONS

Fortunately, catastrophic failures of turbine hot sections are the exceptions, but our goal must be to reduce their number and severity. Because failures represent the experiences and response of the equipment to real world conditions, we cannot afford to ignore the valuable lessons and other information that can be extracted.

Each failure is different. While there are a limited number of basic mechanisms by which gas turbine components can fail, the number of possible combinations of circumstances by which these mechanisms could be brought about is practically limitless. Even with seemingly identical failures on the same model of turbine, site, and user specific factors can have had crucial influences. Comparisons between particular occurrences can clearly be useful, but drawing conclusions based solely on outward similarities should be avoided. Each failure should be individually analyzed using proven methods to properly understand all the causal aspects and, from these, develop the specific corrective measures to avoid costly recurrences.

APPENDIX A
HOT SECTION COMPONENT DEGRADATION/FAILURE MECHANISMS

Creep

Creep occurs when hot section components are subject to high stresses at elevated temperatures for extended periods of time. The higher the stress-temperature combination, the shorter the component life. Current engine designs require the full creep strength properties of the blade alloy to operate reliably. If the properties are reduced due to extended operating times, incorrect heat treatments, or environmental attack, then component failure can occur well before the predicted life has been used up.

Environmental Attack

Turbine hot section components are subject to high temperature oxidation and high and low temperature types of hot corrosion by the combustion gases. Oxidation/corrosion resistant coatings are required on most hot section components, and the effectiveness of these coatings in protecting the base metal from environmental attack has, in many instances, become the principal life limiting factor. Environmental attack, by itself, seldom results in a catastrophic failure, but the damage caused to the components can eventually lead to their failure by some other mechanism.

Thermal-Mechanical Fatigue

Thermal-mechanical fatigue (TMF) damage is associated with high transient or steady-state temperature gradients in the component that results in differential thermal expansion of the material. When free expansion cannot occur as a result of the part geometry, high stresses and strains are generated. The highest strains usually occur in the hottest and coolest regions of the section. Thermal fatigue life is almost always surface related and is generally correlated with the number of startup and shutdown cycles.

High Cycle Fatigue

High cycle fatigue failures can occur as the result of the application of repeated or fluctuating stresses, typically associated with aerodynamic effects and machine vibration. In general, if the fluctuating forces are high enough or if the blade is excited at a resonant frequency, cracks can develop and grow to failure very rapidly. Successful blade designs operate at stresses below those where fatigue cracks are caused. Abnormal conditions, such as large combustor temperature spreads and flow blockages or FOD in highly stressed areas, can raise the cyclic stresses enough to produce fatigue cracks.

Foreign Object Damage

Foreign object damage (FOD) occurs when objects in the gas path strike the rotating blades, usually causing dents, cracks or loss of material. The source for turbine FOD is from improperly secured hardware or failures that release pieces upstream, for example in the combustion system.

Mixed Mode Failures

It is often seen that more than one damage mechanism has contributed to a failure. For example, the "less damaging" mechanisms, such as wear, FOD, erosion, or environmental attack, particularly where localized, can change the stress conditions in a component leading to cracking and subsequent failure by fatigue, creep, or overload.

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